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3 **APPLICATION**

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6

7 *by*

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14 *on the invention entitled*

15 **MANUFACTURING METHOD FOR HIGH YIELD RATE OF**
16 **METAL MATRIX COMPOSITE SHEET PRODUCTION**

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MANUFACTURING METHOD FOR HIGH YIELD RATE OF METAL MATRIX COMPOSITE SHEET PRODUCTION

BACKGROUND OF THE INVENTION

1. Field of the Invention

The present invention generally relates to the methods of batch processing powder-metallurgy (P/M) aluminum alloy and metal matrix composite (MMC) sheet and plate products. More particularly, the present invention relates to the method of manufacturing such product at yield rates higher than conventional batch processes.

2. Description of the Prior Art

Powder-metallurgy MMC's are advanced composite materials that are made from metal powders and reinforcement materials by powder-metallurgy manufacturing methods. P/M MMC can be produced in many forms, such as extruded tubes and rolled sheets.

P/M MMC sheets have many applications in aerospace such as skins and control surfaces, and in the nuclear industry as neutron absorbing material. Each of these applications uses MMC for its special properties which are controlled by different MMC compositions. However, all P/M MMC sheet products produced by prior-art manufacturing methods suffer from low production yield rates from the initial cylindrical shaped billets.

1 Typical sheet yield-rates are approximately 30 to 60% from an initial MMC
2 billet. The higher the percentage of reinforcement in the MMC, the lower the
3 recovery rate for MMC sheet production. The low sheet yield rate reduces
4 productivity and increases cost, and also generates large quantities of scrap. The
5 scrap cannot be recycled as composite and must be recycled as dirty metal, which
6 severely reduces the recovery price. The matrix metal is usually recovered.
7 However, the expensive reinforcing material such as boron carbide is removed
8 with the flux and discarded. As a result, low yield rate and high cost-of-production
9 in current manufacturing processes have limited the applications of MMC sheets,
10 even though they have properties superior to conventional metallic sheets.

11
12 There have been many efforts to make metal matrix composites, as
13 demonstrated in, for example: United States Patent No. 4,104,061 issued to
14 Roberts; United States Patent Nos. 4,557,893 and 4,623,388 issued to Jatkar *et al.*;
15 United States Patent No. 4,946,500 issued to Zendalis *et al.*; United States Patent
16 No. 4,722,751 issued to Akechi; United States Patent No. 5,561,829 issued to
17 Sawtell *et al.*; United States Patent No. 5,965,829 issued to Haynes *et al.*; and
18 United States Patent Application No. 60/387,781 filed by Harrigan *et al.* However,
19 none of these works addressed the manufacturing problem of low yield rate for
20 P/M MMC sheet production.

21
22 A typical prior-art manufacturing process for P/M MMC sheet production is
23 illustrated in Figure 1, often called the billet-extrusion-rolling (BER) processing.
24 An initial cylindrical MMC billet is extruded into a rectangle-shaped workpiece
25 followed by hot rolling to the desired thickness. The extrusion process is used not
26 only to convert the billet into an easily rolled product form. It also imparts thermo-
27 mechanical work to the MMC which improves its mechanical properties leading to
28 improved rolling behavior.

1 The extruded rectangle workpiece possesses a nose defect at the lead end
2 and pipe defect at the butt end. The nose defect manifests itself as a radiused
3 leading edge that has little or no hot work and must be removed during the
4 preparation of the roll preform. The pipe defect is a linear discontinuity that occurs
5 because the center of the MMC billet flows faster than the outside due to friction
6 between extrusion press container, the die surface and the MMC billet.

7
8 If a MMC workpiece is rolled without the nose defect removed, significant
9 edge cracking may develop during the rolling process which reduces the recovery
10 rate. If a MMC workpiece is rolled without the pipe defect removed, the final
11 sheet product will contain a large delamination near the centerline of the thickness.
12 Therefore, the nose and pipe defects must be removed from the extrusion in order
13 to produce good quality sheet. Material losses associated with the extrusion
14 process are about 15 to 18%.

15
16 Edge cracking of the MMC roll-preform occurs during the rolling process.
17 Edge cracks are caused by the limited ductility of the MMC, high shear stresses in
18 the work piece, and the low working temperature at the sheet edges. An edge crack
19 can be as long as 15cm (~6") from the rolled sheet edges. Edge cracking during
20 the rolling process can represent approximately 28% of the weight of the MMC
21 roll-preform, and they must to be removed from the final sheet product before
22 delivery to the customer.

23
24 A "picture frame" rolling method is used to roll materials that have limited
25 ductility. The method uses a metallic picture frame surrounding the material to be
26 rolled. The picture frame and roll preform are rolled together as an assembly. The
27 frame minimizes or prevents rolling edge cracks.

1 For example, United States Patent No. 4,705,577 issued to Ondracek *et al.*
2 and United States Patent No. 4,634,571 issued to Langhans *et al.* described the
3 picture frame method to roll nuclear fuel composites. The frame is retained as part
4 of the final product.

5
6 A picture frame rolling method has been used for rolling aluminum MMC
7 (Al-MMC) sheet. A machined aluminum frame was heated and an Al-MMC
8 rectangular roll-perform was placed inside the frame. As the frame cooled, it
9 shrank to a tight fit around the rectangle Al-MMC. The framed Al-MMC was
10 heated and rolled with multiple passes on a rolling mill to final thickness. The
11 aluminum frame did not retain a tight fit with the rectangular Al-MMC roll
12 preform during all rolling passes because the frame was not metallurgically bonded
13 with the Al-MMC. Therefore, edge cracks, although reduced in length, occurred
14 during the rolling process.

15
16 There is also a “box-frame” method used to produce a MMC sheet. Blended
17 boron carbide and aluminum powder is loaded to a welded aluminum box. The
18 mixture is compacted at room temperature and an aluminum lid is welded in place
19 to seal the box. The box-frame with the blended powder mixture is heated and
20 then rolled to produce a MMC sheet with monolithic aluminum cladding
21 sandwiched on either side of a MMC core that is not fully densified. Such
22 sandwich sheet has poor mechanical and thermal properties and suffers from
23 delamination and blistering problems in corrosive environments. As a result,
24 sandwich sheets have limited applications.

25
26 Therefore, there is a real need to improve the manufacturing technology for
27 MMC sheet, with the specific objective being improved yield rates.

SUMMARY OF THE INVENTION

The present invention is a novel and unique method of manufacturing powder-metallurgy (P/M) metal matrix composite (MMC) sheets.

According to the method of the present invention, hot-pressed P/M MMC billets are directly rolled to P/M MMC sheets, bypassing the extrusion process and therefore avoid the approximately 18% yield loss associated with the extrusion process.

The present invention method produces a square or rectangular P/M MMC billet with a metallurgically bonded metal frame incorporated during the billet manufacturing process. The framed MMC billet can be rolled to sheet without edge cracks.

The manufacturing process of the present invention includes the following major sequential steps:

- (a) Blending of MMC raw materials;
- (b) Preparation of the metal frame and billet consolidation tool;
- (c) Loading and compaction of the blended powders;
- (d) Consolidation of the framed-compact to form the framed-billet;
and
- (e) Rolling of the framed P/M MMC billet.

The main advantage of the present invention is that the sheet yield rate from MMC billet, according to the present invention method, is approximately 80 to 100% compared to 30 to 60% in prior-art manufacturing methods.

BRIEF DESCRIPTION OF THE DRAWINGS

Referring particularly to the drawings for the purpose of illustration only and not limitation, there is illustrated:

FIG. 1 is an illustrative diagram showing a prior art manufacturing process; and

FIG. 2 is an illustrative diagram showing the present invention manufacturing process.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

Although specific embodiments of the present invention will now be described with reference to the drawings, it should be understood that such embodiments are by way of example only and merely illustrative of but a small number of the many possible specific embodiments which can represent applications of the principles of the present invention. Various changes and modifications obvious to one skilled in the art to which the present invention pertains are deemed to be within the spirit, scope and contemplation of the present invention.

The major sequential steps of the manufacturing method of this invention are illustrated in Figure 2, including:

Step 1: Blending of MMC Raw Materials

Matrix metal powder and reinforcement material are blended uniformly at room temperature to produce the MMC mixture.

The matrix metal powder is selected from the group consisting of aluminum, magnesium, copper, iron, zinc, nickel, cobalt, titanium, and alloys thereof. The matrix metal is in particulate form. The average particle size is less than approximately 100 microns.

The reinforcement material is selected from the group consisting of silicon carbide, silicon nitride, titanium nitride, titanium carbide, titanium silicide, molybdenum silicide, nickel aluminate, boron carbide, aluminum nitride,

1 aluminum oxide, magnesium oxide, gadolinium oxide, ceramic materials and
2 mixtures thereof. The reinforcement is also selected from the group of aluminum,
3 boron, cobalt, copper, iron, magnesium, nickel, silicon, titanium, zinc, alloys and
4 mixtures thereof.

5
6 The reinforcement material can have the physical shape of particulate,
7 whiskers, fibers, and mixtures thereof. The average particle size in particulate form
8 is less than approximately 100 microns.

9
10 The matrix metal powder makes up between about 55 and 95 volume percent
11 of the mixture. The reinforcement makes up between about 5 and 45 volume
12 percent of the mixture.

13
14 **Step 2: Preparing the Metal Frame and Billet Consolidation Tool**

15
16 A metal cubic cylinder that has a removable bottom is prepared as a billet
17 consolidation tool. A four-sided picture frame made of a metal similar to the
18 matrix metal is placed in the billet tool. The outside walls of the picture frame are
19 in close contact with the inside walls of the consolidation tool. A common
20 lubricant such as that in forging processes can be applied on the inside walls of the
21 consolidation tool for easier removal of the framed MMC billet after hot-pressing.

22
23 The picture frame can be configured such that the frame can act as the billet
24 consolidation tool. Therefore, the separate billet consolidation tool is not
25 necessary for supporting the picture frame. If the framed MMC billet is designed
26 to be rolled in only one direction, only the two roll-preform sides that are parallel
27 to the rolling direction are necessary to be framed because the other two sides will
28 not have edge cracks during the one-direction rolling.

1 All sides of the MMC billet can be framed to form an encapsulating box-
2 framed MMC billet for rolling as well. The box-framed MMC billet is rolled to
3 produce sandwich structure sheet that has thin skins of the frame metal and a MMC
4 core that is about 100% theoretical density. The skins and the MMC core are
5 metallurgically bonded. This sandwich MMC sheet will not have blistering or
6 delamination problems.

7
8 Of course the frame shape is not limited to square and rectangle. Round and
9 other shapes are possible if they are needed.

10
11 **Step 3: Loading and Compaction of the Blended Powders**

12
13 The powder mixture is loaded to the frame and then is compacted at room
14 temperature to form a framed-compact that is approximately 50% to 95% of the
15 theoretical density.

16
17 **Step 4: Consolidating the Framed-compact to Form a Framed-Billet**

18
19 This step consolidates the framed MMC compact to form a framed-billet.
20 The frame is also metallurgically bonded to the MMC billet during the operation.

21
22 There are various powder metallurgy methods to consolidate the framed-
23 compact to form the framed-billet. The following are typical processes:

24
25 (1) Vacuum/Inert-gas/Air Hot-Press

26
27 Under vacuum, inert-gas or air, the framed-compact is heated to a degassing
28 temperature range and then is held in the temperature range for more than about

1 one-half hour for degassing. The degassing temperature range depends on the
2 matrix metal and is from between about 230°C (450°F) and less than the lowest
3 eutectic melt temperature of elemental powder in the matrix metal. The main
4 function of degassing is to remove H₂O from the MMC compact.

5

6 After the degassing period, the temperature is raised to the consolidation
7 temperature, which is the highest eutectic melt temperature of elemental powder in
8 the matrix metal. The consolidation temperature is lower than the melt temperature
9 of the basic matrix metal. The consolidation temperatures are between about 230
10 and 615°C (450 and 1145°F) for aluminum MMC. While the consolidation
11 temperature and vacuum, inert-gas or air are maintained, the degassed-compact is
12 pressed to full density resulting in a framed-billet.

13

14 In the case of only one element metal in the matrix metal is used, the
15 consolidation temperature is bellow the melt temperature of the element metal.

16

17

18 (2) Cold Isostatic Press/Sinter

19

20 In the Cold Isostatic Press/Sinter process, the MMC mixture is compacted at
21 room temperature in Step C to about 85% to 95% of theoretical density. Pressing
22 the powder mixture to high density at room temperature requires pressures between
23 about 50,000 psi and 85,000 psi. Typically, a cold isostatic press (CIP) is
24 employed.

25

26 The framed-compact is then sintered in vacuum, in inert-gas or in air. The
27 framed-compact is heated to the degassing temperature range and then is held at
28 this temperature range for more than about one-half hour to be degassed. After

1 degassing, the degassed-framed-compact is heated to a sintering temperature that is
2 the highest eutectic melt temperature of the elemental powder in the matrix metal
3 so that sintering of the matrix takes place to form the framed-billet. This sintered
4 MMC billet has a density that is still approximately that of the starting compact
5 between 85% and 95% of the theoretical density, but is sealed by the sintering
6 process. This sealing is needed to avoid internal oxidation of the billet during
7 heating for rolling. The MMC sheet density is approximately 100% of theoretical
8 density after the sintered billet is rolled.

9

10 CIP/Sinter is not suitable to produce P/M MMC that has only one elemental
11 matrix metal because there is no transient eutectic melt required for sintering of
12 matrix metal,

13

14 (3) Cold Compacting/Hot Press

15

16 The framed-compact produced in Step C is heated to the consolidation
17 temperature in inert-gas or in air. While the consolidation temperature and inert-
18 gas continue to be maintained, the framed-compact is hot pressed to approximately
19 98 to 100% of theoretical density to produce the framed-billet. There is no
20 degassing period required in this process.

21

22 Step E: Rolling Framed-Roll-preform

23

24 The framed-billet is cleaned to produce a framed-roll-preform. The cleaning
25 operation includes removing excessive frame metal from bottom and top surfaces
26 and cleaning the roll surfaces by sandblasting, chemical mill or machining as
27 necessary.

1 The framed-roll-preform is rolled to sheet according to a rolling schedule. If
2 two-direction rolling is needed, the framed-roll-preform is rolled in one direction
3 to produce the desired sheet width and then is rolled in the other direction to
4 produce the desired length and final thickness.

5
6 The rolled frame metal is removed for recycling. The finished MMC sheet
7 is then cut to final dimension.

8
9 Theoretically, the MMC sheet recovery rate could be up to 100% from the
10 initial MMC powder mixture by the manufacturing method defined by this
11 invention because of no in-process MMC loss. Practically, however, recovery
12 rates of between about 80 and 95% are achievable.

13
14 What is believed to be the best mode of the invention has been described
15 above. However, it will be apparent to those skilled in the art that numerous
16 variations of the type described could be made to the present invention without
17 departing from the spirit of the invention. The scope of the present invention is
18 defined by the broad general meaning of the terms in which the claims are
19 expressed.

20
21 Of course the present invention is not intended to be restricted to any
22 particular form or arrangement, or any specific embodiment, or any specific use,
23 disclosed herein, since the same may be modified in various particulars or relations
24 without departing from the spirit or scope of the invention hereinabove shown and
25 described of which the apparatus or method shown is intended only for illustration
26 and disclosure of an operative embodiment and not to show all of the various forms
27 or modifications in which this invention might be embodied or operated.

1 The present invention has been described in considerable detail in order to
2 comply with the patent laws by providing full public disclosure of at least one of
3 its forms. However, such detailed description is not intended in any way to limit
4 the broad features or principles of the present invention, or the scope of the patent
5 to be granted.

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